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Photonic Nanojet in Non-spherical Micro-particles

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***Abstract*-We present the first photonic nanojet analysis in the non-spherical micro-particles. The electric intensity distributions in the vicinity inside and outside a non-spherical micro-particle have investigated by using the finite-difference time-domain calculation. The non-spherical micro-particle is truncated by the cutting thickness. The shape dependence of the photonic nanojet has been investigated by numerical calculation. The results have a significant impact on the use of photonic nanojet to identify nanoscale optical imaging.**

Keywords-Photonic nanojet; micro-particle; subwavelength

I. INTRODUCTION

The observation of subwavelength targets with conventional lenses is difficult because of the diffraction limit [1,2]. There is a fundamental maximum to the image resolution of any optical apparatus which is due to diffraction. The evanescent waves store subwavelength message of object and are missed before reaching the image plane. Recently, the phenomenon of photonic nanojets has been studied by several scientific literatures [3-11]. They show that the photonic nanojets are procured on the reverse side of various microspheres under lightwave illumination. The photonic nanojet is a high intensity focusing beam and has a subwavelength waist. The excellent properties of photonic nanojet are a potential utilization to detect nanoscale targets in visible light region. Recently, the super-enhancement of photonic nanojets generated at the shadow side surfaces of a core-shell microcylinder and a graded-index microellipsoid illuminated by a plane wave is presented by the author [12-17]. The power enhancement of photonic nanojet depends strongly on the thickness of metal shell. Therefore, the size dependence of photonic nanojet can be decreased to improve the detection sensitivity in the far-field optical system.

In this paper, we first propose the photonic nanojet analysis in the non-spherical micro-particles. The distributions of the electric field in the vicinity inside and outside a non-spherical micro-particle have simulated by using the finite-difference time-domain (FDTD) calculation. The non-spherical micro-particle is truncated by the cutting thickness. The numerical approximation of photonic nanojet for the non-spherical micro-particle is presented in Section 2. We summarize the results and consider the potential utilizations in Section 3.

II. NUMERICAL APPROACH

The Lorenz-Mie theory is widely used to estimate the spatial distribution of electromagnetic fields in the vicinity of a dielectric microsphere exposed to lightwave illumination. The total optical field is separated into the incident, internal, and scattered fields with respect to the microsphere in this theory. However, the optical properties of a photonic nanojet are affected by other factors that the Lorenz-Mie theory does not take into account. The FDTD calculation [18] is a accurate numerical method that allows computer-aided design and simulation of photonic nanojets in the dielectric microspheres. In this paper, we study the internal and near external field distributions of plane wave illuminated dielectric non-spherical micro-particle by using high resolution three-dimensional (3-D) FDTD calculation to solve Maxwell's equations. The computational domain is a cubic box in the 3-D simulation. The lattice space increments are Δx, Δy, and Δz in the x, y, and z coordinate directions. The centered finite difference expressions is used for the space and time derivatives that are both calculated and second-order accurate in the space and time increments.

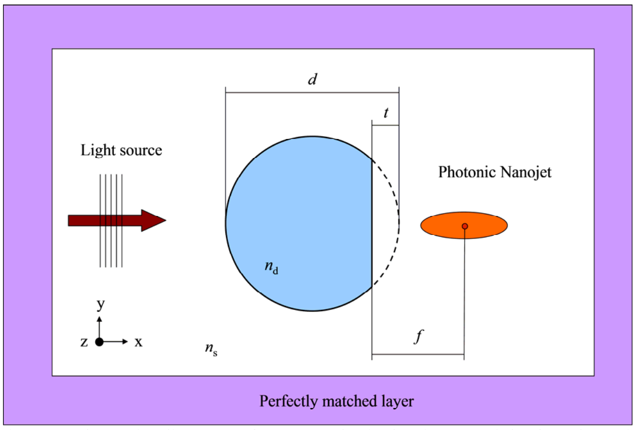
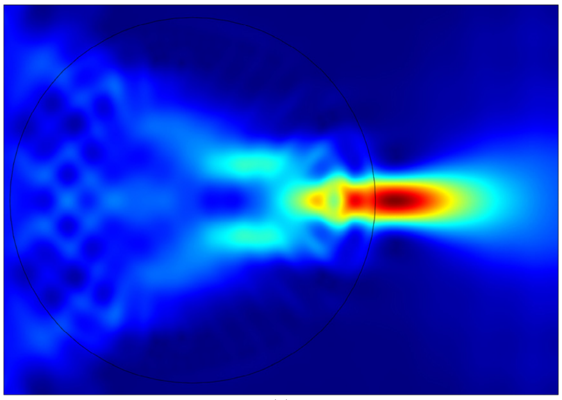
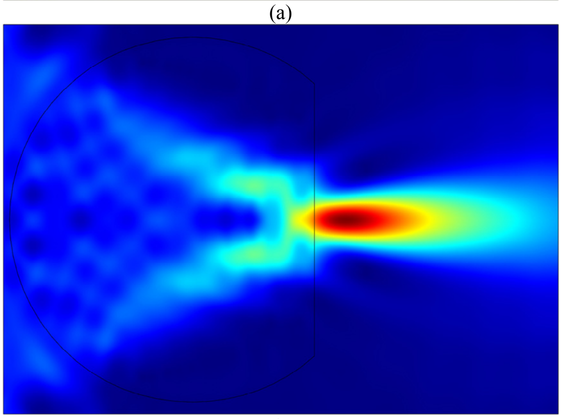


Fig. 1. Schematic diagram of a non-spherical micro-particle for photonic nanojet.

The application of photonic nanojet has been limited by the short length of nanojet. The short length only allows photonic nanojet to detect the near surface features. Therefore, we are interested in photonic nanojet analysis for far-field projection. In this aim, a non-spherical micro-particle for nanojet is proposed by the authors. Figure 1 shows a non-spherical micro-particle for photonic nanojet. The refractive indices of the particle and surrounding medium are n_d =1.6 and n_s = 1. The diameter of particle is *d* and the cutting thickness is *t*. The focal length from the surface of the particle to the point of maximum intensity of nanojet is *f*. Light beam with wavelength 633 nm propagates from left to right.



(a)



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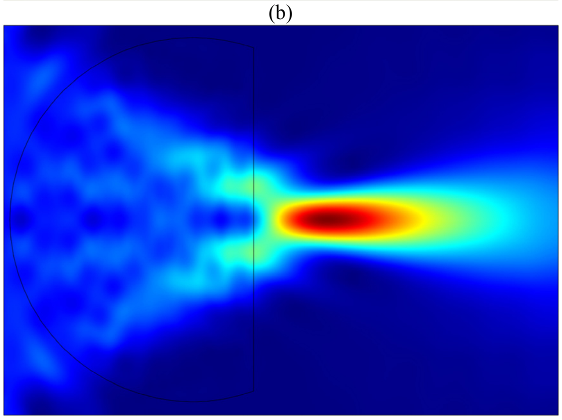

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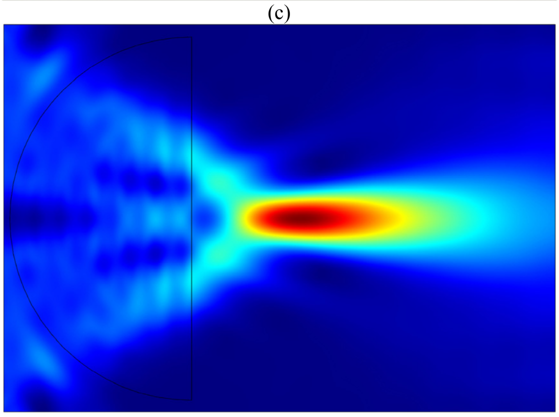

(d)

Fig. 2. Power flow patterns of non-spherical micro-particles at cutting thickness (a) $t = 0$, (b) $t = 500$ nm, (c) $t = 1000$ nm, and (d) $t = 1500$ nm.

Many papers exhibit how the dimension of the photonic nanojet can be adjusted by different generating microspheres. The photonic nanojets with high intensity can exist in both the internal and external fields along the incident direction. We use Matlab code to construct three-dimensional finite-difference time-domain computational model and investigate the photonic nanojet property in the non-spherical micro-particles. Figure 2 shows the power flow patterns of non-spherical micro-particles at different cutting thicknesses. A plane wave with an initial wavelength 532 nm is incident from the left and impinges on the non-spherical micro-particle. It can be seen that the length of photonic nanojet is elongated greatly at t = 1500 nm. The location and the intensity of these near field photonic nanojets depend on the shape of dielectric microsphere. Depending on the shape type of micro-particle, we observe that not only the dimensions and intensity of photonic nanojet change but the separation of the nanojet from the micro-particle surface changes also. At cutting thickness t = 1500 nm, the photonic nanojet adhered to the outer surface of the micro-particle and emerges from it in the form of the exponentially decaying trail. In addition, the longitudinal electromagnetic distribution of photonic nanojet becomes more complex.

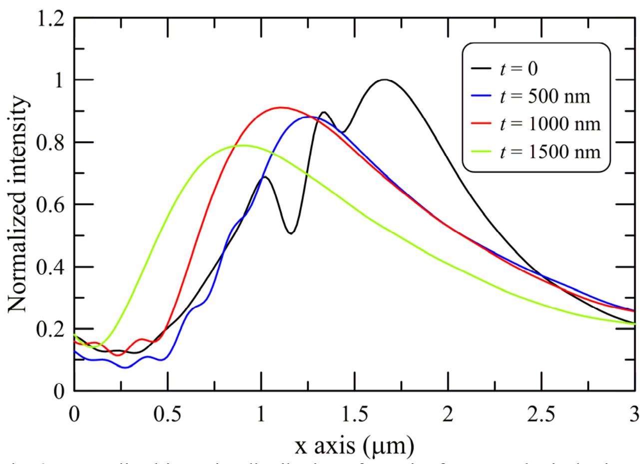

Fig. 3. Normalized intensity distribution of nanojet for non-spherical micro-particles along propagation axis.

It is necessary primarily to define spatial length and width to investigate the characteristics of photonic nanojet. Figure 3 shows the normalized intensity distribution of photonic nanojet for non-spherical micro-particles along propagation axis. The longitudinal profile is received as a section of the two-dimensional intensity distribution by the straight line located at y = 0, while the transverse profile is received as a section by straight line parallel to the y axis and passing through the peak of the maximum intensity of photonic nanojet. The all intensities of photonic nanojet for non-spherical micro-particles are normalized to the intensity for the dielectric microsphere in the same diameter. The non-spherical micro-particles at cutting thickness t = 1500 nm demonstrate longest and low-intensity photonic nanojet with the extent of about 5λ. Figure 4 shows the normalized intensity distribution of nanojet for non-spherical micro-particles along transversal axis. It is significant that we have smallest transverse width of photonic nanojet among all considered situations, which does not exceed the incident lightwave. The location and length of the photonic nanojet depend on the cutting thickness of the micro-particles, but the full-width half-maximum of photonic nanojet is almost the same at the different cutting thicknesses.

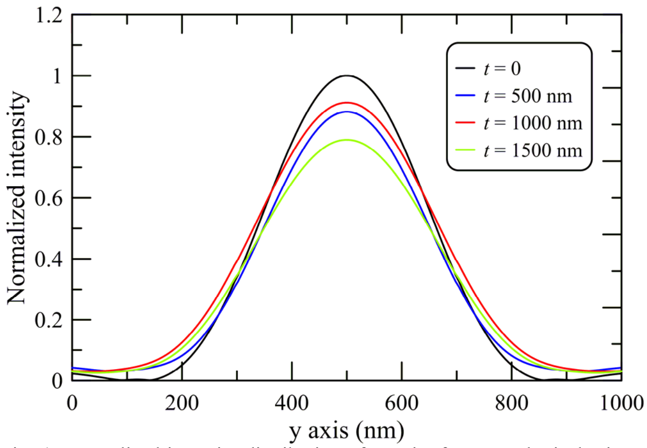

Fig. 4. Normalized intensity distribution of nanojet for non-spherical micro-particles along transversal axis.

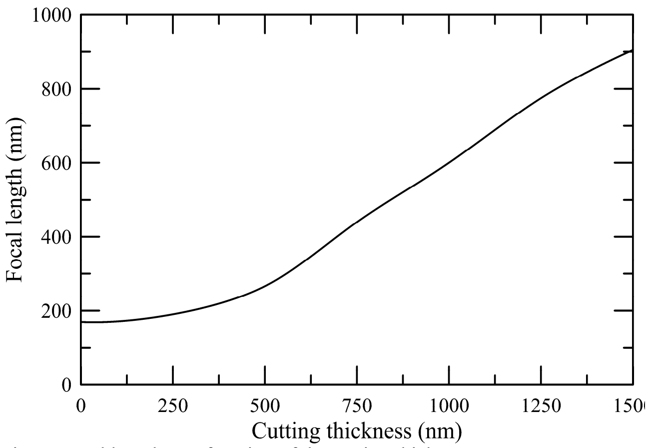

Fig. 5. Focal length as a function of the cutting thickness.

Figure 5 depicts the focal length of nanojet as a function of the cutting thickness. The focal length increases as cutting thickness increases. As a result, the focal length and the location of the nanojets can be controlled by cutting thickness. This morphological type of non-spherical micro-particles optimally combines the high spatial localization of the photonic nanojet with sufficiently high power. At large cutting thickness *t*, the photonic nanojet is formed rather far from the shadow of the non-spherical micro-particles, and a decrease in *t* the coordinate of the intensity maximum reaches the micro-particle rim. The optimal balance between the key parameters of photonic nanojet is realized in the non-spherical micro-particles with cutting thickness. The incident beam at wavelength of 532 nm is selected as an example. The photonic nanojet in the non-spherical micro-particles is scalable in respect of the incident wavelength and the diameter.

III. Conclusion

In conclusion, we have numerically analyzed the photonic nanojets generated at the shadow side surface of a non-spherical micro-particles illuminated by a plane wave. The basic characteristics (focal length, peak intensity, and intensity distribution) of photonic nanojets formed in the vicinity of dielectric non-spherical micro-particles with different types of cutting thicknesses by using high resolution FDTD calculation. It is possible to modulate the photonic nanojet abnormally. The latitudinal and longitudinal dimensions of a photonic nanojet and its peak intensity depending on the cutting thickness of non-spherical micro-particles are numerically investigated. We can gain control of the parameters for photonic nanojet through the variation of the cutting thickness of non-spherical micro-particles. This physical phenomenon could be an important implement in the fields of nano-optics and nano-biotechnology. The observed optical emission suggests the possible use of these non-spherical micro-particles as a super lens corresponding to the number of micro-particles arranged in the photonic molecule. The photonic nanojet may permit coupling of lightwave from the photonic molecule into other photonic micro- or nano-devices such as coupled resonant optical waveguides or nano-coaxial cables. The devices would be not only with sub-wavelength spatial accuracy, but also with extremely high intensities in comparison with traditional sub-wavelength coupling techniques using scanning near-field optical microscopic tips. The ultimate state will verify the ability of photonic nanojets to measure nano-scale surface features within inhomogeneous objects.

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